International Journal of Agricultural
Science and Research (IJASR)
ISSN(P): 2250-0057; ISSN(E): 2321-0087
Vol. 4, Issue 3, Jun 2014, 27-44

BIOPHYSICAL AND CROP MANAGEMENT GRADIENTS LIMITING YIELDS OF EAST AFRICAN HIGHLAND BANANA (MUSA SPP. AAA-EA) WITHIN FARMS IN LOW INPUT CROPPING SYSTEMS

ISAAC NEWTON ALOU[1], PIET J.A VAN ASTEN[2] & MOSES MAKOOMA TENYWA[3]

[1]Bulindi Zonal Agricultural Research and Development Institute, Hoima Uganda

[2]International Institute of Tropical Agriculture, Kampala Uganda

[3]Faculty of Agriculture, Makerere University, Kampala, Uganda

ABSTRACT

The study aimed to quantify the relative contributions of soil fertility factors (*S*), pests and diseases (P) and crop management practices (*M)* to highland banana (*Musa* spp. AAA-EA) yields under heterogeneous on-farm conditions. Soil status, nutrient levels, pests, crop management from 150 mats within close (CH), mid (MH) and remote (RH) distances of 10 homesteads in Butare, Southwest Uganda were monitored from 2006-2008. Actual yields (14.3 Mg ha^{-1} yr^{-1}) of dominant cultivar (cv. 'Enyeru') were limited by *S* (62.8%), *P* (22.0%) and *M* factors (15.2%). Bunch mass was limited by low soil pH (< 6.2), low exch. Ca (< 2.04 $cmol_+kg^{-1}$), Mg (< 2.3 $cmol_+kg^{-1}$), high K:Mg ratio (0.99±1.2), mat density (> 1512 mats ha^{-1}) and excessive defoliation (< 9 functional leaves) from boundary line analysis. DRIS norms of exchangeable bases were low relative to N, P & K. Banana weevil and nematode damages contributed 21.7% and 3.3% of yield limitations, respectively. Most *S* factors limited yields in 'fertile' CH (75%) and *P* factors in MH and RH which differed with household resource endowment. Spatial variability in biophysical factors within small farms is so large and should be considered when addressing yield limitations to highland banana yields.

KEYWORDS: Within-Farm Variability, Relative Distance, Yield Limitation, Constraint, Wealth Class, East African Highland Banana, Uganda

INTRODUCTION

Banana (*Musa* spp.) is ranked among the four most important food crops and is a staple food for millions of people worldwide. Ten percent of the world banana output is produced in Uganda (FAO, 2001) where banana is synonymous to food. Per capita consumption of bananas estimated as 220-460 kg per annum in Uganda (FEWSNET, 2004) is the highest figure in the world. Most production occurs in the backyards of smallholder farms often referred to as 'homestead gardens' and average plantation size is less than 0.5 ha (Gold et al.., 1999). Bananas are common sights within close proximity of most rural homesteads in Southwest Uganda. Actual highland banana yields on-farm in Central (3.1-12.4 Mg ha^{-1} yr^{-1}) and in Southwest Uganda (9.7- 20.0 Mg ha^{-1} yr^{-1}) (Smithson et al., 2004; Wairegi et al., 2007) are still far from potential yield of 60-90 Mg ha^{-1} yr^{-1} (van Asten et al., 2004). The causes of low banana yields such as soil fertility decline and a complex of pests and diseases differ between regions, agro-ecological zones and farms. A spiral shift in banana production in recent decades in Uganda from traditional coffee-banana system to cattle-millet systems supports is explained by differences in constraints to banana production.

Previous studies on yield loss factors in bananas (e.g. Rukazambuga et al., 1998; Talwana et al., 2003; Gold et al., 2004) often focused on a single constraint and trials were conducted on-station. However, yield limiting factors are intricately interwoven (Smithson et al., 2001; Okech et al., 2004) and interactions of factors were not adequately investigated. In most studies, it was also ‘assumed’ that yield limiting constraints, other than the one investigated as either homogenous between plots and treatments or as insignificant. In many cases, specific pest constraints for example Radopholus Similis, Pratylenchus goodeyi (Speijer et al., 1999, Talwana et al., 2003) and Cosmopolites Sordidus (Gold et al., 2004) were further increased in certain treatments by introduction of eggs, larvae and adults. Banana yield loss due to factors from most studies cannot be extrapolated to heterogeneous on-farm conditions characterized by differential crop management (Schlecht et al., 2006; Zingore et al., 2007).

Strong banana performance gradients characterized by decreasing crop performance with increasing distance from the homestead have been observed in East African (Bosch et al., 1996; Bekunda, 1999). Crop productivity gradients within smallholder farms are sometimes linked to differences in soil fertility management when moving away from the homestead. Farmers find it convenient to dispose organic matter and wastes such crop residues, wood ash and kitchen refuse in contiguous locations to homesteads. Although such crop gradients have been observed, they have rarely been quantified in detail in relation to banana growth and yields. Okech et al. (1996), Gold et al. (1999) and Okech et al. (2006) tried to explain variability in banana yields between farms and not within farms. At farm level, variability in crop performance is supposedly higher within than between farms and regions. It is thus not surprising that previous studies had difficulty relating crop yield variables to yield limiting constraints such as root nematodes, banana weevils and soil fertility. Variability in crop yields between farms may be caused by differences in physiographic location and by differences in management practices (Deckers, 2002 cited by Tittonell et al., 2006) which may be influenced by differences in resource endowment (Rubaihayo et al., 1994).

Objectives and Hypotheses

The main objective of the study was to quantify the relative contribution of biophysical and crop management in explaining spatial gradients in banana yields between and within farms with different household resource endowment and physiographic location. The specific objectives were:

- To determine the contribution of soil fertility properties, farmer management, banana pests and diseases to the yield gap in the farmers’ field.
- To establish the interactions between soil fertility properties, banana pests and diseases within farms.
- To determine within-farm variability in banana yields and constraints among farmers belonging to the different wealth classes.

The study tested the following hypotheses:

- Soil fertility factors and banana pests contribute additively to farm banana yields.
- Banana yields and soil fertility decrease and pest pressure increases when moving from the kitchen garden to areas further away from the homestead.
- The magnitude of within-farm variability in yields will be smaller in resource wealthier farms because input use is higher and more evenly distributed within rich farms.

MATERIALS AND METHODS

Site

The study was conducted in Butare valley, Nyakyera sub-county in Ntungamo district in Southwest Uganda where 67% of the Country's banana production occurs (Kangire et al., 2000). The site was chosen due to its agro-ecological characteristics which are broadly representative of the situation found in other tropical highlands of East Africa. The site lies between latitudes 00^{o} 47.88′and 00^{o} 53.79′ S and longitudes 30^{o} 13.66′ and 30^{o} 13.85′E with an average elevation of 1440 masl. Butare valley received average annual rainfall of 1043 mm from weather data of 1999-2006 which according to Taulya et al. (2006) corresponds to a yield loss of 30-40% in highland bananas. The site is characterized by steep topography and evidence of gulleys suggests that erosion is a constraint to banana production. Soils are predominantly sandy loams, formed on granite and quartzite parent rock (Anon, 1962). They are classified as Ferralsols and belong to Buwhezu series (Ollier, 1959) typical of low weatherable mineral reserves (Birabwa et al., 2008). Hence, plant nutrient supply on such soils is largely dependent on organic matter management (NKedi-Kizza et al., 2002) as they are low in exchangeable bases.

Sampling Framework

A baseline diagnostic survey was conducted in 2005 on 50 farms that were randomly selected from the list of households in Butare valley. The survey showed that banana production levels and factors affecting yields varied highly among farmers. Ten out of the 50 farms were selected based on resource endowment level, that is, 3 rich (RF), 4 medium (MF) and 3 poor (PF) and slope position (3 on upper, 4 on middle and 3 on lower). The provisional wealth class were developed based on farm typology that distinguished farms using local criteria obtained during Participatory Rapid Appraisal (PRA). On each farm or homestead, 15 mats or stools of the dominant cooking banana cultivar (cv. 'Enyeru') were selected following a range of relative distances (RD) from the homestead, that is, close (CH), mid-distant (MH) and remote (RH). The shortest distance of the mat from the kitchen, the main source of organic inputs was measured before mats were grouped into RD or plots.

Monitoring of Banana Mats and Field Observations

Composite soil samples (0-30 cm) were collected from five random sub-samples around each mat at the start of the study in mid 2006. Soils were analyzed for pH (water) using a 1: 2.5 H_2O/water suspension, % C using H_2SO_4-acid acid-dichromate digestion (Walkey-Black method), total N was determined calorimetrically after Kjedahl digestion and Mehlich-3 extraction mixture for cations (Ca^{2+}, Mg^{2+} and K^{+}) and available P. Texture was determined using the hydrometer method (Anderson and Ingram, 1993). The host farmers were entirely responsible for management of their plantations, so no treatments or recommendations were imposed. Banana crop management practices and most prevalent pests and diseases were monitored for two entire crop cycles.

The performance of each plant was monitored from date of appearance to date of harvest maturity. Plant spacing was determined by measuring the distance to the four nearest mats. The mat area was demarcated using pegs as the area of uniformity around the plant where crop management properties were taken. The following observations were made for each mat area on a monthly basis: weed coverage (%) and height (cm), mulch thickness (cm) all taken from five random points along two axes of the mat using a tape. The intercrop presence, type, and plant density were recorded within each mat area. Organic inputs and fertilizer application frequency were also recorded and from farmer records. Plant

observations were done on monthly basis with respect to leaf pruning and severity of Banana streak virus (BSV) and leaf spots following Stover scale (1971). The youngest spotted leaf was used as an index for black Sigatoka (Mycosphaerella fijiensis) severity according to Marin et al. (2003). Nematode root necrosis was determined at flowering in a 20x20x20 cm pit near the base of the flowering plant according to Speijer and De Waela (1997) and Carlier et al. (2002). Plants were harvested when farmers perceived bunches as being mature. Farmers' criterion related to ripening of the first fingers in the bunch. Foliar samples (0.1 by 0.2 m strips) of inner lamina of leaf 3 at bud emergence (Martin-Prével et al., 1979) were analyzed for N, P, K, Ca, Mg and Zn. The norms and critical values developed for highland bananas in Uganda (Wairegi et al., 2007) were used to establish the most limiting nutrient (s). Weevil corm damage to harvested stands or pre-mature stands was assessed at harvest using the cross-sectional method (Gold et al., 1994; Speijer and Gold, 1996). Weevil associated damages were also recorded during the study.

Statistical and Boundary Line Analyses

Correlation and regression were performed using SPSS Release 11 for Windows (SPSS Inc. 2001) to identify the relationships between all biophysical properties with yields. The most significant relationships were identified after checking using scatter plots and box plots before boundary line analysis (BOLIDES). The BOLIDES approach as opposed to traditional regression is based on Von Liebig's 'law of the minimum', there is one factor limiting crop performance at a time. The line represents the maximum response or yields that can be attained at any level of environmental properties (Schnug *et al.,* 1996).

A boundary function is written as $Y = Min\{f(X_1), f(X_2), \ldots f(X_N)\}$ where Y refers to yields (in this case bunch mass of bananas) determined by yield-influencing factor present in (relative) minimum amount; and $f(X_i)$ is the maximum attainable yields from an independent variable i = 1, 2,3,…N (e.g. soil pH and weevil damage). The minimum yield predicted by single response functions at each RD was taken to be the yield prediction at that location. From 150 mats monitored across 15 farms, predictions were made on each mat before grouping into RD as plots. The approach was used to partition the contribution of soil nutrients, pests and diseases and crop management practices to yield loss.

Differences in yield variables and constraints between wealth classes were assessed using Least Squared Differences (LSD) after analysis of variance with RD as a sub-plot treatment, farmer resource endowment level as a main plot and individual farm as a replicate or block using SAS version 9.1 (SAS® Institute Inc. 2003). The Levene's test of homogeneity of variance (Levene, 1960) in One-way ANOVA (in randomized blocks) was performed for hypotheses of equal variability of yield(s) within farms from three wealth classes.

RESULTS

Banana (cv. Enyeru) Growth and Yields within and across Farms of Different Resource Endowments

Within the farms, irrespective of wealth class, growth and yield components tended to increase from remote (RH) through mid-distant (MH) to the close (CH) areas of the homesteads. However, significant differences were only observed for plant height (P = 0.001), girths at base (P = 0.003) and at 1 m (P = 0.01) and number of fingers per bunch (Table 1). The number of fingers per bunch were significantly (P = 0.018) lower in RH than for CH. All plant growth properties at flowering were significantly strongly (P < 0.01, r > 0.70) correlated with bunch mass (results not shown). Considering wealth class, most growth and yield properties except the number of fingers per bunch tended to increase from

resource- poor through the medium to the rich farms but no significant differences ($P > 0.05$) across the wealth classes. Bunch mass from rich farms in particular was 0.4 kg bigger than from medium ones and 0.7 kg bigger than poor ones. The number of fingers per bunch was significantly higher from the resource rich farms than from poorer ones. There was no significant interaction ($P > 0.05$) between relative distance and wealth classes on all growth properties. The within-farm variation in growth properties (girths at base and at 1 m) only was not significant among of MF. Growth properties at flowering and bunch characteristics at harvest were however more variable among the resource poor than among medium and rich farmers (results not shown). The homogeneity test showed that the number of clusters per bunch varied significantly (Levene's test, $P = 0.038$) highly within farms of the resource poor than of medium and rich ones, respectively.

Table 1: Selected Banana (cv. Enyeru) Yield Trends by Relative Distance from Homestead between Farms

Nr. of Obs. (n)	Distance Class[‡]	Average D from Homestead (Metres)	Girth at Base (cm)	Girth at 1m (cm)	Height (cm)	Fresh Bunch Mass (kg)	Nr. of Fingers Per Bunch	Nr. of Hands per Bunch
71	CH	20.9±9.2	79.5±10.5 ^{a}	55.7±9.4^{a}	377.0±39.1^{a}	14.37±4.64	113.0±32.7^{a}	7.8±0.7
73	MH	37.2±12.4	77.8±10.5^{a}	55.4±9.2^{a}	369.0±43.6^{a}	13.88±3.62	111.7±37.6^{ab}	7.4±0.8
79	RH	37.2±12.4	74.0±9.1^{b}	51.8±7.2^{b}	352.9±30.8^{b}	12.26±4.07	98.5±30.9^{b}	7.1±0.8

Means within a column followed by the same letter are not significantly different; [‡]Actual distance related to distance between a mat and the kitchen, which was major source of organic inputs in the households, n refers to number of mats for two crop cycles

Relationship between Biophysical Factors and Banana Yields

Strong fertility gradients characterized by decreasing levels of most soil fertility properties were observed with increasing distance of the mat from the homestead (Figure 1). Mean levels of pest damage tended to be higher CH than MH and RH (results not shown). Soil fertility properties (*S*), pests and diseases (*P*) and crop management practices (*M*) were significantly correlated to fresh bunch mass and total above-ground dry matter (ABG) (Table 2) and other yield components including number of fingers and clusters per bunch.

Most *S* factors were positively correlated to bunch mass with the exception of the K/Mg ratio and percentage clay content which were negatively correlated. Surprisingly, no significant correlations appeared between soil exchangeable K and most bunch yield variables. Soil K was only related to girth at base ($P < 0.01$, $r = 0.42$) and at 1m ($P < 0.05$, $r = 0.32$) at flowering. Among *P* factors, only weevil corm damage and nematode root necrosis were significantly negatively correlated to bunch mass. The *M* factors which were significantly correlated to bunch mass were only mat density ($r=-0.31$) and number of functional leaves at flowering ($r =0.58$).

Table 2: Selected Relationships between Biophysical Factors and Banana Yield Variables at Harvest

Biophysical Factor	Mean±S.D	Pearson's Correlation Coefficient	
		Bunch Mass (kg)	ABG Dry Matter (kg)
Soil Attribute[†]			
SOM (%)	3.8±2.1	0.36*	0.46**
Total N	0.16±0.09	0.42**	0.43**
Exch.Ca	2.94±2.6	0.60**	0.633**
Exch. Mg	2.16±1.9	0.51**	0.57**

Table 2: Contd.,

K/Mg ratio	0.99±1.2	-0.41**	-0.42**
Clay (%)	23.1±3.9	-0.42**	-0.33*
Pest damage (%) Weevil corm damage	7.39±9.2	-0.31*	-0.27*
Nematode root necrosis	6.39±3.63	-0.36*	-0.43*
Crop management indices Mat density (mats ha^{-1})	2836 ± 1152	-0.31**	-0.13*
No. functional leaves at bud emergence	8.8±1.99	0.58**	0.46**
Weed factor	563.2±450.6	n.s.	-0.34*

† Mean for soil properties (n = 150 samples); n.s. = not significant, *significant at P = 0.05 and at **significant at P = 0.01

ABG stands for above ground biomass

Contribution of Factors to Yield Limitation of Banana

Some biophysical factors that were significantly correlated to banana yield variables did not appear as limiting bunch weights from BOLIDES. Boundary line analysis revealed that soil fertility properties collectively were the most important factors that constrained yield, contributing to 62.8% of total yield limitations. Pests and diseases accounted for 22.0% and crop management practices 15.2% of total yield limitations. The regression model of bunch mass with measured independent variables was highly significant ($R^2 =0.54$; *** $P < 0.000$). The highest variability in bunch mass was explained by *S* ($R^2 =0.328$; ** $P < 0.01$), followed by *M* ($R^2 =0.223$; ** $P < 0.000$) and *P* ($R^2 =0.108$; ** $P < 0.044$).

Soil Fertility Properties

Soil fertility properties which limited banana yield and contribution to total yield limitations were high K/Mg ratio (20%), low soil pH (18.3%), high clay fraction (10.0%), low exchangeable Ca (10.0%) and low Mg (1.7%) and Ca/Ca+Mg+K (3.3%). Total soil N, SOC and most nutrient ratios computed were only significantly correlated to yields but were not yield limiting. Bunch mass response to soil pH indicates that yields were enhanced with increase in pH values especially in the range 5.0-6.2 (Figure 2). Bunch mass attained in the second upper pH quartile (6.3 - 6.9) was equivalent to a yield increase of 53.8% relative to the mean bunch mass of 13.2 kg, obtained in the lower pH quartile (5.0-5.6). There was no yield increase detected beyond pH 6.2 with increase in pH from 6.9 to 7.4.

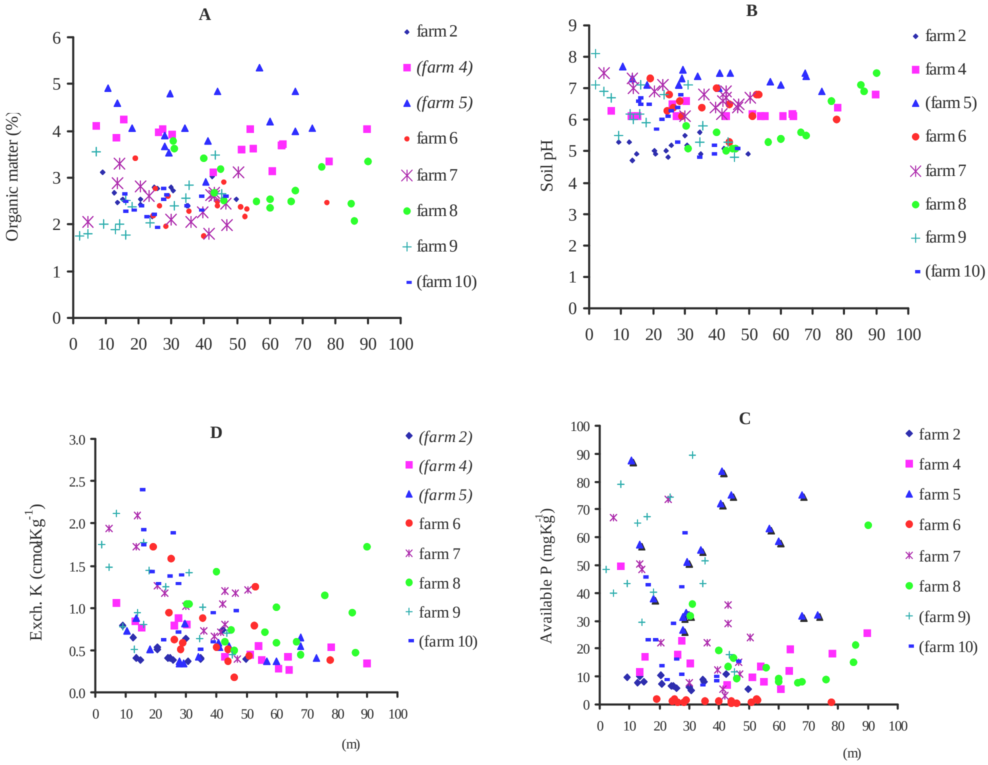

Figure 1: Soil Fertility Gradients within Farms (n = 120 Composite Samples). Relationships between Selected Soil Properties, Soil Organic Matter (A), pH (B), Available P (C) and Exchangeable K (D) with Distance (Metres) from the Kitchen. Parenthesis () Indicates Significantly (P > 0.001, Dunnett's t-Test) Different Farms for Each Property. Farms in Italics are not Significantly (P > 0.001) Different by the Same t-test of Group Comparison

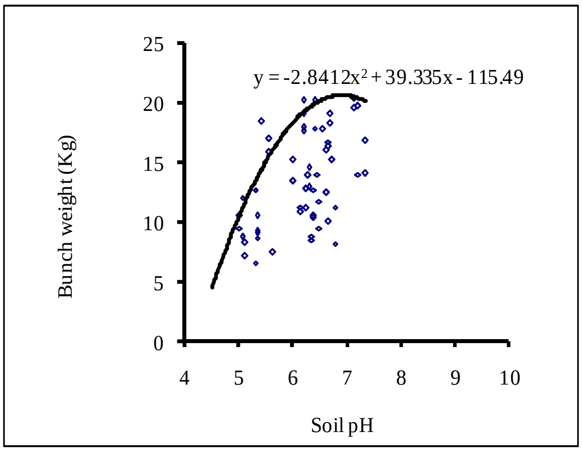

Figure 2: Boundary Line Showing Bunch Mass Response to Soil pH

Bunch mass appeared to strongly decrease (R^2 = 0.85) with increase in percent clay contents of surface soil. The predicted mean bunch mass of 21.7 kg as the maximum value on the response function is however constant for clay fractions between 18.5% and 21.4% (Figure 3).

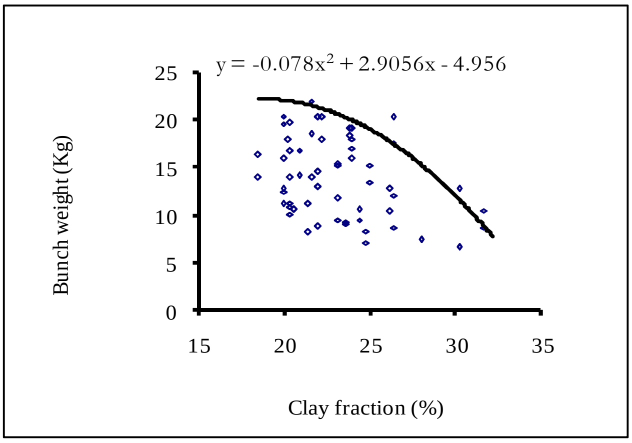

Figure 3: Boundary Relationship between Banana Bunch Mass and Soil Clay Contents

A strong response of bunch mass to soil exchangeable Mg occurred at levels between 0.36 – 1.04 $cmol_+kg^{-1}$ indicating a limitation to yield improvements occurred at low Ca concentrations (Figure 4).

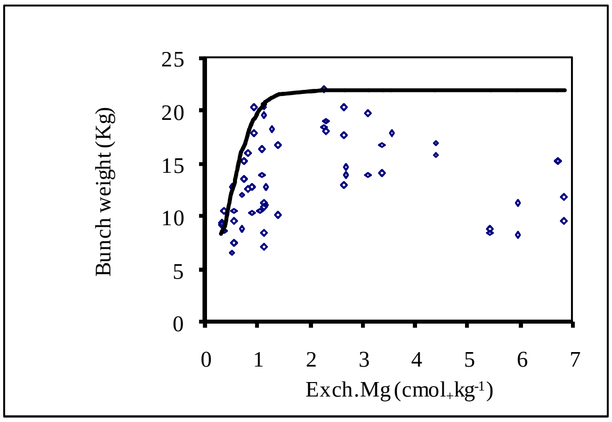

Figure 4: Boundary Relationship between Bunch Mass on Soil Exchangeable Mg

There was no increase in bunch mass with further increase in soil Mg levels above 2.3 $cmol_+kg^{-1}$ which corresponded to higher values of Mg ratio with K. Bunch mass was drastically reduced as K/Mg ratios increased (Figure 5).

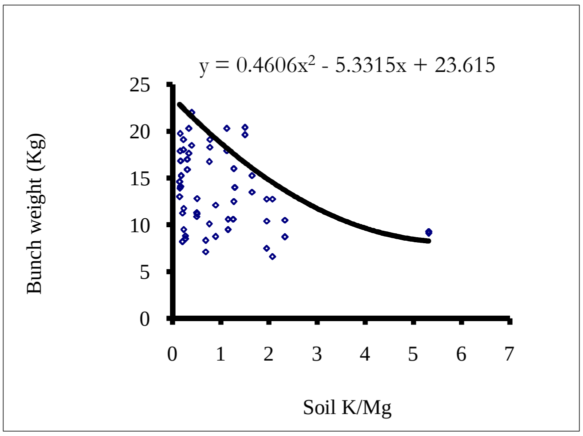

Figure 5: Bunch Mass Response to Ratios of Soil K/Mg

A similar pattern to soil Mg was observed for exchangeable calcium. Bunch mass increased strongly at Ca levels less than 2.04 $cmol_{+}kg^{-1}$ (log-phase) and then slightly to a maximum of 22.0 kg at level of 2.11 $cmol_{+}kg^{-1}$ above which bunch mass remained constant (Figure 6).

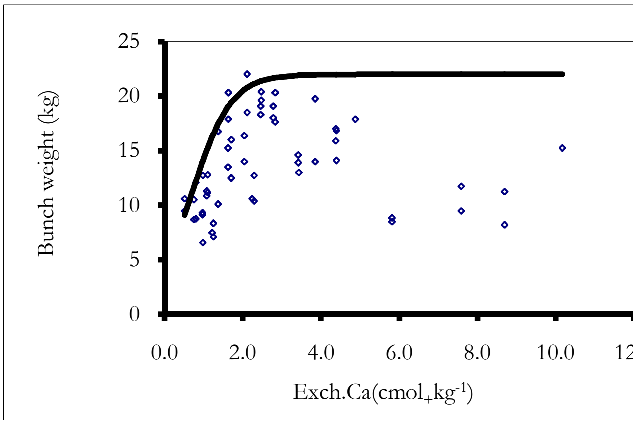

Figure 6: Boundary Response of Bunch Mass on Soil Exchangeable Ca

Pests and Diseases

Banana weevil (*C. sordidus* Germar Coleoptera) was the single most important limitation to yields of all factors contributing to 21.7% of the total yield limitations besides other yield losses. Bunch mass decreased linearly with increasing weevil damage on harvested plants. Total corm necrosis (0 - 66.5%) averaged 7.4%. By approximation, plants with the highest weevil damage at harvest had bunch mass reduced by 41.9% relative to bunch mass from ones with no corm damage (Figure 7). Heavy damage of banana weevil resulted in additional yield losses including disappearance of 8 mats (out of 150) in both ratoons and loss of 2 plants through snapping. Cross-section corm necrosis in plants which died averaged 34.2% but extremely damages of 95% corm necrosis was also assessed in some plants.

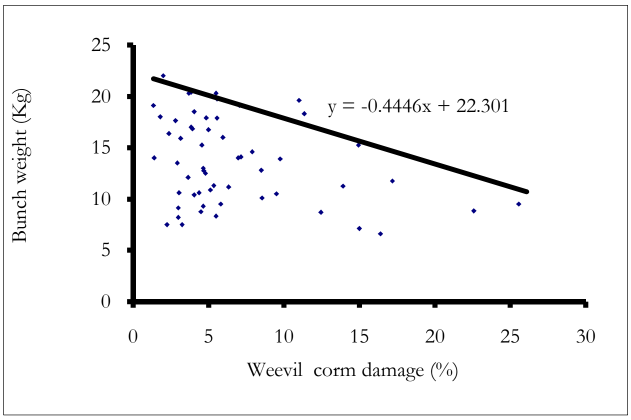

Figure 7: Relationship between Bunch Mass and Weevil Necrosis at Harvest

Root nematodes caused toppling of 8 (5.3%) and 11 plants (7.3%) in starting and follower ratoons, respectively. The parasites in addition contributed to 1.67% limitations in bunch mass. Bunch mass strongly decreased ($P < 0.05$, $R^2 = 0.76$) with nematode root necrosis ranging 0 -17% (mean = 6.4%) at flowering.

The most common diseases, Banana streak virus and leaf spots did not limit yields but reduced bunch mass by 21.5% and 16.9%, respectively in severely infected plants compared to disease-free ones. Disease severity

(score low, moderate & severe) except for Black Sigatoka, did not significantly (P > 0.05) depress bunch mass (results not shown). Black Sigatoka was observed on only 5% of the total plants monitored and symptoms occurred on the youngest leaf number 8, 6 and 10 in an order of increasing frequency. The mean number of clusters per bunch in particular was more by one in plants without Black Sigatoka symptoms compared to those with severe symptoms.

Farmer Crop Management

Crop management practices which had an impact on yields were leaf pruning, mat spacing and weeding. About twelve percent (11.67%) of the total yield limitations in bunch mass were attributed to few functional leaves. Bunch mass were enhanced with more number of leaves indicative of an exponential increase from (11.0 kg) at 6 leaves to 18.5 kg at 8 leaves (Figure 8).

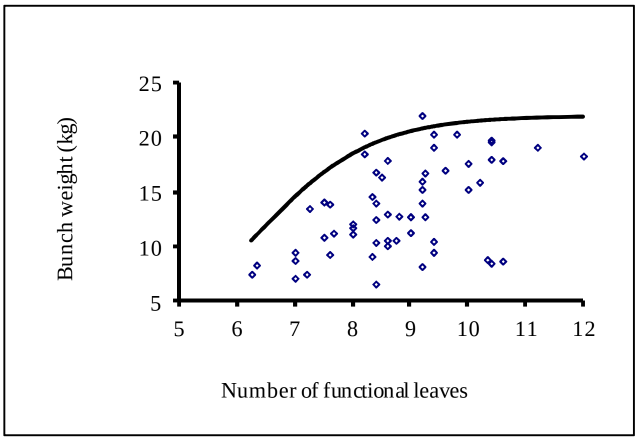

Figure 8: Relationship between Bunch Mass and Number of Functional Leaves at Flowering

The maximum bunch mass of 21.9 kg occurred at a mean of 9 leaves at flowering (Figure 8). Although mat spacing did not limit yields in any relative distances, boundary line (Figure 9) revealed that bunch mass could be maximized at 2.6 m × 2.6 m spacing which is equivalent to 1512 mats ha^{-1}.

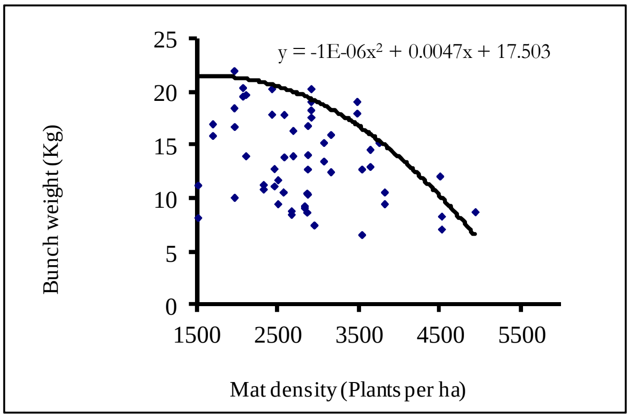

Figure 9: Boundary Relationship between Bunch Mass and Banana Mat Density

Differences in Banana Yield Loss Factors by Wealth Class

The factors which limited banana yields among resource rich farms were different from those which restricted yield improvements among medium and poor ones. Further, the levels of limiting factors were significantly (P < 0.05)

different across wealth classes but not between distance classes of homesteads. For instance, soil pH limited yields in plantations of only poor. Low soil pH constrained yields in all distance classes from their homesteads of the PF. Mean soil pH was significantly ($P < 0.05$) lower in plantations of the PF than in those of wealthier farms (Table 3). Exchangeable Ca in addition constrained yields with significantly lower Ca levels in PF than in plantations of either medium or rich farms. On the converse, soil K/Mg ratio limited yields in plantations of rich and medium farmers but not close distances to their homesteads.

Table 3: Mean (±s.d.) of Selected Yield-Determinants by Level of Farmer Resource Endowment

Factor	Wealth Class		
	Poor	Medium	Rich
Nr. of observations (n)	81	132	51
Soil pH	5.8±0.7 ^{a}	6.2±0.5 ^{b}	6.5±0.7 ^{b}
Exch.Ca ($cmol_+kg^{-1}$)	1.94±1.17^{a}	1.58±0.58^{b}	2.88±1.41^{c}
Exch. Mg ($cmol_+kg^{-1}$)	1.66±0.93^{a}	0.94±0.31^{b}	1.92±1.35^{ab}
Nematode root necrosis (%)	7.3±2.7^{a}	7.2±1.9^{a}	4.6±1.0^{b}
Weevil corm damage (%)	4.9±3.7^{a}	9.9±8.4^{b}	5.2±1.94^{a}
Plant density (plant ha^{-1})	3884±649^{a}	2655±442^{b}	2716±323^{b}

Likewise, the contribution of factors collectively to yield limitations differed among wealth classes and also with distance from homestead. Poor farmers had the highest yield limitations (83.3%) attributed to *S* compared to 63.3% and 41.7% for MF and RF, respectively. The resource wealthier farmers thus had pests, particularly banana weevil as the most critical constraint. With respect to distance class, yield limitations attributed to *S* were mostly confined in CH (75%) compared to 50% in RH. Pests yield limitations in CH accounted for 20% of total limitations, 40% limitations occurred in MH and 40% in RH areas.

Figure 10 shows the yields at RD level or relative yield decline attributed to biophysical factors (soil properties, pests, diseases and crop management) in Southwest Uganda. The model predictions indicate that the r-square value is a good fit of the model.

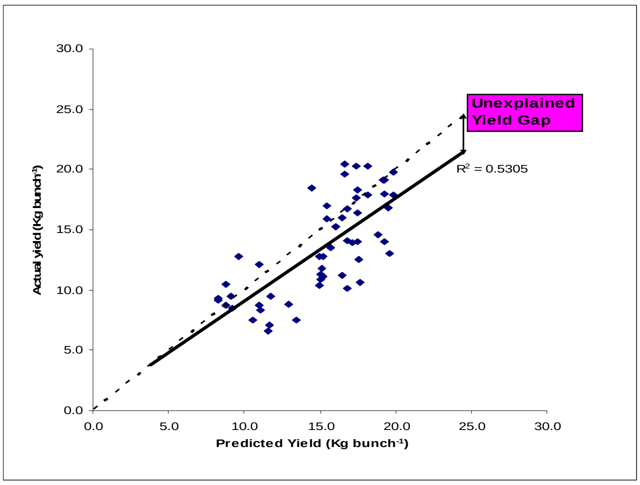

Figure 10: Yield Potentials of Highland Bananas Determined by Boundary-Line Model

DISCUSSIONS

Banana performance varied as a function of distance class from the homestead which confirms the hypothesis that within-farm variability in banana yields is largely related to management gradients. Soils on the farms were sandy.

Textural analysis revealed that soils within farms are of similar inherent fertility based on low percentage (34.3±5.0) of silt+clay which did not change across RD from the homestead. Low levels of exchangeable bases, total N and soil pH have been associated with inherent an infertile soil (Zingore et al., 2006) which is also evident in the banana system. Henceforth, nutrient availability in soils of poor inherent fertility is highly dependent on organic matter management. It was anticipated that ‘man-made’ soil fertility/nutrient gradients which usually relate to distance ‘effects’ from the homestead (Vanlauwe et al. 2006) would strongly correlate to banana performance.

Correlation analysis shows that most soil properties except exchangeable K are highly correlated to banana yields. The lack of correlations between yields and soil K could be attributed to cation imbalance particularly high K/Mg ratio (0.99±1.2) which was far above the optimum K:Mg ratio of 0.3: 1.0 for bananas (Delvaux, 1995).

Boundary line analysis revealed that within S factors, high K/Mg was the most important limiting factor followed by low soil pH and low exchangeable Ca. Bunch mass limitations at low pH corresponding to exponential phase is a reflection of the effect of pH on nutrient availability to plants (Tisdale et al., 1990). The effect was supported by positive significant ($P < 0.01$) correlations between soil pH with foliar P ($r = 0.45$), K ($r = 0.35$) and with Ca ($P < 0.05$, $r = 0.20$). The hindrance to yield improvements at low pH could also be attributed to toxicity of Mn and Al ions which occurs below pH 5.5 (Tisdale et al., 1990). On the other hand, K-Mg imbalance restricted possible yield improvements at high pH values. The relationship of bunch mass and soil pH strongly support the need for liming to overcome hindrances to yield improvements. The drastic decrease in bunch mass with increase in percent clay could be interpreted as more soil physical problems such as poor aeration and penetration to banana root development (Gauggel et al., 2005) and nutrient imbalance from higher K but not Ca and Mg with more clay in top soil.

Boundary line functions seem to suggest critical values for banana production as Mg (2.3 $cmol_{+}kg^{-1}$), Ca (2.04 $cmol_{+}kg^{-1}$) and soil pH (6.2). It is worth noting that ranges for soil properties except for K were below the optimum ones established by Lopez and Espinoza (2000). According to ‘The Law of the minimum’ (Von Liebig, 1863), soil K was too adequate to limit yields based on its concentration (mean = 0.92±0.49 $cmol_{c}kg^{-1}$) which is greater than critical levels of 0.32-0.74 $cmol_{c}kg^{-1}$ (Landon, 1991). Potassium sufficiency was confirmed by no foliar K deficiencies from DRIS analysis which were positive, that is, 5.6 in RH, 9.1 (MH) and 9.2 (CH) moving away from the homestead. It was thus not surprising that low soil K was not among the constraints to yields although it is frequently most deficient in most banana areas (Smithson et al., 2001). The correlations of K detected with banana growth parameters support its importance in particularly determining pseudostem girth (Murray, 1960). Absence of N deficiencies (DRIS indices = 5.4, 6.1, 6.6) also confirms lack of limitations associated with total soil N. Except foliar K, the indices for leaf Ca (-8.2, -7.5, -7.9) and for Mg (3.7, 1.5, 0.8) moving away from homestead confirmed the yield limitation due to low soil exchangeable bases. We could not explain why foliar P deficiency indicative of negative DRIS indices (-6.5, -9.2, -8.7) occurred and yet soil P status not correlating to yields.

Weevil damage at harvest was high when compared to threshold levels of 5.0% cross-section damage and 3.0% damage to the central cylinder (Gold et al., 1999). Banana weevil thus caused significant reductions in bunch mass and accounted for highest yield losses because damage disrupts water and nutrient uptake besides reducing plant anchorage. Results support previous on station in trials in a different agro-ecological zone (Rukazambuga et al., 1998; Gold et al., 2004) which indicated that banana weevil causes great yield losses when damage is high. Nematodes are not minor constraints *per se* as they could cause more significant reductions in bunch mass when the damage is high. Although

the mean necrosis is slightly higher than the thresh hold level of 5% in banana plantations (Speijer et al., 1994), Gowen et al. (2005) considers root necrosis of less than 25% as a slight damage to plants. Therefore, bunch mass limitations and 'qualitative' yield losses attributed to nematodes in this study are unexpected. Like weevils, nematodes have an indirect effect of dry matter production by damaging the root system.

Yield limitation of few functional leaves was purely a crop management aspect because neither soil nutrient concentrations nor damage by pests were correlated to number of green leaves. The importance of number of functional leaves at flowering in banana yields (Robison, 1996; Smithson et al., 2001) has been shown in earlier studies (Shatyarayana, 1986; Pillai and Shanmugavelu, 1987) elsewhere and in Uganda by Tushemereirwe (1996). The studies related few functional leaves to foliar disease severity. However in this study, the low number of functional leaves was attributed to deliberate defoliation by the farmers. Past studies showed leaves are fewer due to foliar diseases (Karamura and Karamura, 1995) and due to weevil attack (Rukazambuga et al., 1998). Bunch mass can be maximized with low mat density at a spacing of 2.6 m × 2.6 m (1512 mats ha^{-1}) instead of the recommended 3 m × 3 m (1111 mats ha^{-1}) by NARO (1998).

Factors for yield loss tended to be influenced by the level of farmer resource endowment. Higher values of soil pH and levels of exchangeable bases in resource wealthy than poorer farms could be interpreted as a long-term consequence of dumping kitchen refusals (wood ash, vegetable matter and food wastes, poultry and animal manures) and crop residues in the backyards. The impact of disposed materials on the soil fertility is hypothetically stronger in plantations belonging to the rich farms that generate more quantity of household wastes compared to poorer farms. The high soil K/Mg ratio in rich farms could have resulted from banana residues largely fruit peelings, which are rich in K (van Asten et al., 2004). Large quantity of residues were likely generated from rich farms because they had bigger plantations (0.43 ha) compared to those of medium (0.36 ha) and poor (0.26 ha) farms. Consequently, the rich had most yield limitations of high soil K/Mg ratio. Overall, findings suggest that low soil fertility as opposed to pests is a critical limitation to yield improvement among poor farmers than among medium and rich ones.

The boundary model predicted yields adequately (R^2 = 53.05%) similar to other studies that have used this methodology. The unexplained yield gap of 47% is due to other factors that were not accounted in the study notably soil water which according to Taulya et al. (2006) can greatly limit banana yields in the rainfall patterns of the study site. The approach has been used in explaining sorghum yield response to soil properties (Shatar and McBratney, 2004), partitioning rice yield-gap to soil properties (Casanova et al., 1999) and banana yields to biophysical factors (Okumu, 2007). It should be noted that the explained variance in yields is within and not between farms because the multivariate model considers each point in the field separately. Hence, overcoming constraints to banana yield improvements should take into account the large variability within farms.

CONCLUSIONS

Actual highland banana yields (14.3 t $ha^{-1}yr^{-1}$) in low input systems in Southwest Uganda were mostly constrained by soil fertility properties accounting for 62.8% of yield limitations, pests 22.0% and crop management practices 15.2%. High K/Mg ratio and low soil pH were the critical soil fertility constraints followed by low Ca and low Mg. Soil organic matter, total soil N and exchangeable K were not surprisingly non-limiting factors because the two nutrients were not even deficient in leaves and were well balanced. The effect of soil K/Mg on yields was influenced by soil pH and liming is paramount to correct problems of low soil Mg. Banana weevil singly accounted for the highest yield limitations

in bunch mass plus other yield loss losses and could be regarded the most important constraint in bananas. Excessive leaf pruning by farmers contributed to yield limitations of crop management.

Banana yields varied as a function of farmer resource endowment level and improvements can be affected by household wealth class. The number of clusters per bunch was a better indicator of yield variability than bunch mass. Growth parameters at flowering and number of fingers per bunch between distance classes reflected the impact of management gradients within farms. Poor farmers had most limitations attributed due to low soil pH and inadequate Ca. Their plantations were more severely deficient in foliar Ca compared to those of wealthier farms. In contrast, yields in medium and rich farms were constrained by mostly pests (banana weevil) and high soil K/Mg ratio. Findings provide a comprehensive understanding on the magnitude of yield loss in highland bananas under a wide range of biophysical factors. The information provides a basis for informed decision making on resource allocation and choice of practices for improvement of banana yields among smallholder farms. Soil fertility practices which raise soil pH and improve availability of exchangeable bases (Ca^{++}, Mg^{++}, and K^{+}) are more critical in resource poor farms. Controlled experiments but exploiting heterogeneous conditions on farms are required to confirm the threshold levels of each limiting factor.

ACKNOWLEDGEMENTS

The authors are grateful to farmers of Butare in Ntugamo district for support rendered during the survey and monitoring study. We are also very grateful to the research team; particularly Mr. Walusimbi T. K. Mugaaga (RIP) and staff of TSBF-CIAT Analytical Laboratory Nairobi who assisted in conducting the diagnostic survey and in laboratory analysis respectively. Special thanks to administrative staff of IITA-ESARC (Uganda) for supporting the student during his M.Sc. studies at Makerere University.

REFERENCES

1. Anderson, J.M., Ingram, J.S.I. 1993. Tropical Soil Biology and Fertility: A Handbook of Methods. CAB International, Wallingford, UK
2. Anonymous. 1962. Atlas of Uganda. Department of Lands and Surveys, Entebbe, Uganda. 83 p
3. Birabwa, R., van Asten, P.J.A., Alou, I.N. & G. Taulya. (2008). Got Matooke (*Musa* spp.) for Christmas? Acta Hort., 113-122
4. Carlier, J., De Waele, D. & Escalant, J.V. (2002). Global Evaluation of *Musa* Germplasm for Resistance to Fusarium wilt *Mycosphaerella* Leaf Spot Diseases and Nematodes. In: Vezina and Picq, C. (Eds.) INIBAP Tech Guidelines 6. Montpellier, France, 68
5. Casanova, D., Goudriaan, J., Bouma, J. & Epema, G.F. (1999). Yield gap analysis in relation to soil properties in direct-seeded flooded rice. *Geoderma* 91, 191–216
6. Deckers, J. (2002). A systems approach to target balanced nutrient management in soilscapes of sub-saharan Africa. In: Vanlauwe, B., Diels, J., Sanginga, N. & Merckx, R. (Eds.). Integrated Plant Nutrient Management in Sub-Saharan Africa. CAB International, Wallingford, pp. 47–61
7. Delvaux, B. (1995). Soils. In: Gowen, S. (Ed.). Bananas and plantains. Chapman and Hall. London. 230-257
8. Gauggel, C.A., Sierra, F & Arévalo, G. (2003). The problem of banana root deterioration and its impact on

production: Latin America's experience. In: Turner, D. W. & Rosales, F. E. (Eds.). *Proceedings of an international symposium, San José, Costa Rica, 3-5 November* 2003. INIBAP: Montpellier, France

9. FAO. (2001). Banana and Plantain Production FAO, 1998. Agricultural Production Statistics Database (FAOSTAT). Food and Agricultural Organization of the United Nations Rome, Italy
10. FEWSNET. (2004). FEWS Uganda Food Security Update November 08 December 2004. Increased movement hampers aid efforts
11. Gold, C.S., Kagezi, G. H., Night, G. & Ragama, P.E. (2004). The effects of banana weevil *Cosmopolites sordidus*, damage on highland banana growth, yield and stand duration in Uganda. *Ann. appl. Biol.*, 145, 263-269
12. Gold, C.S., Karamura, E.B., Kiggundu, A., Bagamba, F. & Abera, A.M. (1999). Geographical shift in the highland cooking banana (*Musa* spp., group AAA-EA) production in Uganda. *International journal of Sustainable Development and World Ecology* 6, 45-59
13. Gold, C.S., Speijer, P.R., Karamura, E.B., Tushemereirwe, W.K. & Kashaija, I.N. (1994). Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Science Journal* 2, 309-321
14. Gowen, S.R. and Quénéhervé, P., & Fogain, R. (2005). Nematode parasites of Bananas and Plantains. In: Lue, M., Sikora, R.A., Bridge, J. (Eds.). Plant parasitic nematodes in Subtropical and Tropical Agriculture. CABI Publishing, UK
15. Karamura, E.B., & Karamura, D.A. (1995). Banana morphology – part II: the aerial shoot. In: Gowen, S. (Ed.). Banana and Plantains, Chapman and Hall, London. 190-205
16. Landon, J.R. (1991). Soil Suitability for Banana (*Musa Sp*). In: Brooker Tropical Soil Manual. J.R. Landon (ed.) Oxon UK: 292-293
17. Levene, H. (1960). Contributions to Probability and Statistics, pp.278–292. Stanford University Press, CA
18. Lopez, A. M., & Espinoza, J. M. (2000). Manual of the Nutrition and fertilisation of banana. Potash and Phosphate Institute and CORBANA., Costa Rica
19. Marin, D H., Romero, R. A., Guzman, M., & Sutton, T. B. (2003). Black Sigatoka: An increasing threat to banana cultivation. *Plant Disease* 87(3), 208-222
20. Martin-Prével, P., Marino. F., & Andres, A.B. (1979). Growth, yield and leaf nutrient content of organically grown banana plants in the Canary islands. Instituto de Productos Naturales y Agrobiología Francisco Sánchez, Spain
21. Murray, D.E. (1960). The effect of deficiencies of the major nutrients on growth and leaf analysis of the banana. *Tropical Agriculture* 37: 97–106. In: Alvarez, C.E., Ortega, A., Fernández, M. & Borges, A. A. (2001). Growth, yield and leaf nutrient content of organically grown banana plants in the Canary Islands. *Fruits* 56, 17–26
22. NARO. (1998). The Republic of Uganda: Banana Production Manual.18 pp
23. Nkedi-Kizza, A., Awuma, J. and Gladwin, C.H. (2002). Gender and Soil Fertility in Uganda: A comparison of soil fertility indicators on women's and men's agricultural plots. *African Studies Quarterly* 6

24. Okalebo, J.R., Gathua, K.W., and Woomer, P.L. (2002). Laboratory Methods of Soil and Plant Analysis: A Working Manual, 2nd edition. Sacred African Publishers, Nairobi, Kenya

25. Okech, S. H., Gold, C. S., Bagamba, F., Masanza, M., Tushemereirwe, W.K. & Ssennyonga, J. (2006). Cultural control of banana weevils in Ntungamo, southwestern Uganda. In: Blomme, G., Gold, C., Karamura, E. (Eds.). *Proceedings of the workshop on Farmer-participatory testing of IPM options for sustainable banana production in Eastern Africa*, Seeta, Uganda, 8 -9 December 2003. INIBAP: Kampala, Uganda

26. Okech, S. H., Van Asten, P.J.A., Gold, C.S., Ssali, H. (2004). Effects of potassium deficiency, drought and weevils on banana yield and economic performance in Mbarara, Uganda. *Journal of Agricultural Sciences* s9, 511-519

27. Okech, S.H.O., Gold, C.S., Speijer, P.R., Karamura, E., Ssali, H. and McIntyre, B. (1996). Relationships between soil fertility, banana weevil, nematodes and agronomic practices in Southwestern Uganda. Musafrica 10, 31

28. Ollier, C.D. (1959). The soils of the Northern Province, Uganda. Uganda Protectorate Department of Agriculture, No. 3. 80 p

29. Pillai, O.A and Shanmugavelu, K.G. (1987). Studies on the effect of the number of functional leaves on flower bud initiation in banana cultivar poovar. *Indian Journal of Horticulture* 34, 358-361

30. Robinson, J.C. (1996). Bananas and plantains. CAB International, Wallingford, UK

31. Rukazambuga, N.D.T.M., Gold, C.S. and Gowen, S.R. (1998). Yield loss in East African highland banana (*Musa* Spp., AAA-EA group) caused by banana weevil, *Cosmopolites sordidus* Germa. *Crop Protection* 17(7), 581-589

32. SAS® 2003. Copy right © 2002 -2003 by SAS Institute Inc., cary, NC, USA. SAS® 9.1 (TSIMO)

33. Speijer, P.R., Kajumba, C. H. and Ssango. (1999). East African Highland Bananas as influenced by nematodes and crop management. *International Journal of Pest Management*, 45 (1) 41-49

34. Satyanarayana, M. (1986). Effects of the number of functional leaves on growth and yield of “Dwarf Cavendish” banana (AAA). Newsletter of the international group on horticultural physiology of banana, University of Western Australia 9, 34-36

35. Schlecht, E. Buerkert, A., Tielkes, E. and Bationo, A. (2006). A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems* 76,109–136

36. Schnug, E., Heym, J. and Achwan, F. (1996). Establishing critical values for soil and plant analysis by means of the Boundary Line Development System (Bolides).

37. Communications in Soil Science and Plant Analysis 27, 2739–2748

38. Shatar, T.M. and McBratney, A. B. (2004). Boundary-line analysis of field-scale yield response to soil properties. *Journal of Agricultural Science 142,* 553–560

39. Speijer, P.R. and De Waela, D. (1997). Screening M*usa* Germplasm for Resistance and Tolerance to Nematodes, INBAP techn. Guidelines 1. INBAP, Montpellier, France.44p

40. Speijer, P.R. and Gold, C.S. (1996). *Musa* root health assessment: a technique for the evaluation of *Musa* Germplasm for nematodes resistance. In: Frison, E.A., Horry, J.P. and De Waele, D. (Eds.). New Frontiers in resistance breeding for nematode, Fusarium and Sigatoka. *Proceedings of a workshop* held in Kuala Lumpur, Malaysia, 2-5 October 1995. INIBAP, Montpellier, France
41. Smithson, P.C., McIntyre, B.D., Gold, C.S., Night, G. & Okech, S.O. (2004). Potassium and magnesium fertilizer on Banana in Uganda: Yields Weevil damage, foliar nutrient status and DRIS analysis. *Nutrient cycling in Agro ecosystems*. In Press
42. Stover, R.H. (1971). A proposed international scale for estimating intensity of banana leaf spot. *Tropical Agriculture,* Trinidad 48: 185-186
43. Talwana, H.L., Speijer, P.R., Gold, C.S., Swennen, R.L., De Waele, D. (2003). A comparison of the effects of the nematodes *Radopholus similis and Pratylenchus goodeyi* on growth, root heath and yield of East African highland bananas (*Musa* AAA-group)
44. Tisdale, S.L., Werner, L.N., Beaton, J.D. (1990). Soil Fertility and Fertilizers 4th edition. New York, Maxwell Macmillan Publishing Company
45. Tushemereirwe, W.K. (1996). Factors influencing the expression of Leafspot diseases of highland bananas in Uganda. PhD Thesis, The University of reading, UK
46. Van Asten, P.J.A., Gold, C.S., Okech, S.H., Gaidashova, S.V., Tushemereirwe, W.K. & De Waele, D. (2004). Soil quality problems in East African banana systems and their relation with other yield loss factors. *The International Journal on Banana and Plantain* 13 (2), 20-24
47. Zingore, S., Murwira, H.K., Delve R.J. & Giller, K.E. (2006). Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *Field Crops Research* 101, 296–305